A Swing-Contract Market Design for Flexible Service Provision in Electric Power Systems

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A Swing-Contract Market Design for Flexible Service Provision in Electric Power Systems

Wanning Li and Leigh Tesfatsion

Abstract The need for flexible service provision in electric power systems has dramatically increased due to the growing penetration of variable energy resources, as has the need to ensure fair access and compensation for this provision. A swing contract (SC) facilitates flexible service provision because it permits multiple service attributes to be offered together in bundled form with each attribute expressed as a range of possible values rather than as a single point value. This paper discusses a new SC Market Design for electric power systems that permits SCs to be offered by any dispatchable resource. An analytical optimization formulation is developed for the clearing of an SC day-ahead market that can be implemented using any standard mixed integer linear programming (MILP) solver. The practical feasibility of the optimization formulation is demonstrated by means of a numerical example.

1 Introduction

The increased penetration of variable energy resources in electric power markets has increased the volatility of net load (i.e., load minus non-dispatchable generation) as well as the frequency of strong ramp events. Variable energy resources (VERs) are renewable energy resources, such as wind and solar power, whose generation cannot be closely controlled to match changes in load or to meet other system requirements.

In consequence, flexibility in ancillary service provision has become increasingly important to maintain the reliability and efficiency of power system operations. This
has encouraged power system operators to introduce new products and market processes designed to permit more flexibility in ancillary service provision, thus enhancing net load following capability [11].

Nevertheless, three important issues arising from increased VER penetration still need to be resolved. First, energy and reserve products are variously defined and compensated across the different energy regions; see, e.g., [6]. This lack of standardization makes it difficult to compare and evaluate the reliability, efficiency, and fairness of system operations across these regions.

Second, product definitions are specified in broad rigid terms (e.g., capacity, energy, ramp-rate, regulation, non-spinning reserve). These rigid categorizations do not permit resources to be further differentiated and compensated on the basis of additional valuable flexibility in service provision, such as an ability to ramp up and down between minimum and maximum values over very short time intervals.

Third, attempts to accommodate new products have led to the introduction of out-of-market (OOM) compensation processes. In 2011 FERC issued Order 755 to address OOM payment problems for one particular product category in U.S. ISO-managed wholesale power markets: namely, regulation with different abilities to follow electronic dispatch signals with high accuracy [7]. However, given its limited scope, Order 755 does not fully eliminate the need in these markets to resort to OOM processes. As stressed in [3], the additional complexity resulting from OOM compensation processes provides increased opportunities for market participants to gain unfair profit advantages through strategic behaviors.

A group of researchers has been working to develop a new swing-contract market design for electric power systems that permits greater flexibility in service provision while at the same time addressing the above three issues [9, 14]. This work builds on important earlier work [1, 2, 5, 12] that stresses the relevance of options and two-part pricing contracts for electricity markets.

The swing contract (SC) proposed in [9, 14] is a contract for energy and reserve whose terms permit a diverse spectrum of services to be offered as ranges of values rather than as point values, thus permitting greater flexibility in their real-time implementation. These offered services might include, for example, ranges for possible start-up times, durations, power dispatch levels, and ramp rates. Simple examples are used to illustrate how the trading of SCs could be supported by a sequence of linked centrally-managed forward markets in a manner that permits efficient real-time balancing of net load subject to system and reserve-requirement constraints. In comparison with existing wholesale electric power market designs, the following key policy implications of this SC market design are highlighted.

- permits full market-based compensation for availability and performance
- facilitates a level playing field for market participation
- facilitates co-optimization of energy and reserve markets
- supports forward-market trading of energy and reserve
- permits service providers to offer flexible service availability
- provides system operators with real-time flexibility in service usage
- facilitates accurate load forecasting and following of dispatch signals
- permits resources to internally manage UC and capacity constraints
• permits the robust-control management of uncertain net load
• eliminates the need for OOM payment adjustments
• reduces the complexity of market rules

Left unresolved in this previous conceptual work, however, is whether the determination of optimal market-clearing solutions for SCs can be reduced to a routine operation suitable for real-world application. The present study provides an affirmative answer to this question for a general SC market design permitting swing contracts to be offered by any dispatchable resource.¹

Section 2 presents and illustrates a standardized form of an SC for the flexible provision of energy and reserve services in electric power markets. Section 3 discusses in broad terms a new market design for the support of SC trading, with a particular focus on an ISO-managed SC Day-Ahead Market (DAM) design that permits SCs to be offered by any dispatchable resource. Key distinctions between this SC DAM design and current DAM designs are highlighted.

Section 4 presents a new optimization formulation for the market clearing of SCs in the SC DAM. This formulation constitutes a mixed integer linear programming (MILP) problem that can be solved by means of the same MILP solution software currently in use for standard Security-Constrained Unit Commitment (SCUC) optimization formulations [4, 8, 13, 15]. More detailed explanations of the objective function and constraints for this new optimization formulation are provided in Section 5. A numerical example is provided in Section 6 to demonstrate the implementation of this new optimization formulation. Concluding remarks are given in Section 7. A nomenclature table listing symbols and symbol definitions is provided in an appendix.

2 Standardized Form of a Swing Contract in Firm Form

Four standardized contracts are proposed in [9] to facilitate energy and reserve trading: namely, firm contracts and option contracts taking either a fixed or swing form. A firm contract (FC) is a non-contingent contract that requires specific performance from both counterparties. In contrast, an option contract (OC) gives the holder the right, but not the obligation, to procure services from the issuer under contractually specified terms. The right can be activated by exercise of the OC at a contractually permitted exercise time, at which point the contractual terms of the OC become firm.

An FC or OC is a fixed contract if each of its contractual terms is expressed as a single value. An FC or OC is a swing contract (SC) contract if at least one of its contractual terms is expressed as a set of possible values, thus permitting some degree of flexibility in its implementation.

For clarity of exposition, this study will focus solely on SCs in firm form that offer a particular spectrum of services. The form of these SCs is as follows:

¹ The present study is a substantial extension of an earlier preliminary study [10] by the authors appearing in an electronic conference proceedings.
In (1), \( t_s \) and \( t_e \) denote specific calendar times expressed at the granularity of time periods of length \( \Delta t \) (e.g., 1h, 1Min), with \( t_s < t_e \). The power interval bounds \( P_{\text{min}} \leq P_{\text{max}} \) can represent pure power injections (if \( 0 \leq P_{\text{min}} \)), pure power withdrawals or absorptions (if \( P_{\text{max}} \leq 0 \)), or bi-directional power capabilities (if \( P_{\text{min}} \leq 0 \leq P_{\text{max}} \)). The down/up limits \(-R^D, R^U\) for the ramp rates \( r \) (MW/\( \Delta t \)) are assumed to satisfy \(-R^D \leq 0 \leq R^U\).

The location \( b \), the start time \( t_s \), and the end time \( t_e \) are all specified as single values in (1). However, the power levels \( p \) and the down/up ramp rates \( r \) are specified in swing form with associated ranges \( \mathcal{P} \) and \( \mathcal{R} \). As discussed in [9], the performance payment method \( \phi \) designating the mode of ex post compensation for actual real-time service performance can take a wide variety of forms, such as a specified flat rate for energy and/or a power-mileage compensation for ramping.

To understand the obligations of the seller and buyer of this swing contract, should it be cleared, a numerical example might be helpful. Consider the following SC offered into an ISO-managed day-ahead market by a market participant \( m \) at an availability price \( \alpha = $100 \), with \( \Delta t = 1h \):

\[
\begin{align*}
    b &= \text{bus } b; \\
    t_s &= 8:00\text{am}; \\
    t_e &= 10:00\text{am}; \\
    \mathcal{P} &= [P_{\text{min}}, P_{\text{max}}] = [10\text{MW}, 40\text{MW}]; \\
    \mathcal{R} &= [-R^D, R^U] = [-38\text{MW/h}, 28\text{MW/h}]; \\
    \phi &= $35/\text{MWh}.
\end{align*}
\]

Under this SC, market participant \( m \) offers to provide power at bus \( b \) from 8:00am to 10:00am on the following day. The power levels at which \( m \) is willing to be dispatched range from 10MW to 40MW, but the required down/up ramp rates \( r \) to achieve these power levels must satisfy \(-38\text{MW/h} \leq r \leq 28\text{MW/h} \). The performance payment method \( \phi \) designates that \( m \) is to be paid the price \( \phi = $35/\text{MWh} \) for each MWh of energy it delivers under this SC. If the SC is cleared by the ISO, then \( m \) is immediately entitled to receive its availability price \( \alpha = $100 \).

Figure 1 depicts one possible power path that the ISO could dispatch in real-time operations, in accordance with the terms of this SC. The (green) area under this
power path is the resulting energy (MWh) delivery, compensated ex post at the rate of $35/MWh.

![Diagram](image)

**Fig. 1** A possible dispatched power path for the SC numerical example

It is the responsibility of market participant $m$ to ensure it is able to fulfill the terms of this offered SC. For example, with regard to physical feasibility, the power delivery start time $t_s=8:00$ am must precede the power delivery end time $t_e=10:00$ am, which is clearly the case; but, in addition, $|t_e - t_s| = 2h$ must be at least as great as $m$’s minimum up time.

With regard to financial feasibility, market participant $m$ should make sure that its availability price $\alpha = $100 is sufficient to cover all costs incurred in order to guarantee it is available to fulfill the terms of the SC. These costs should include avoidable fixed costs, such as start-up/shut-down costs and no-load costs, as well as lost opportunity costs arising from $m$’s inability to receive revenues for its services in a next-best alternative use. Moreover, $m$ should ensure that its offered performance price $\phi = $35/MWh guarantees full coverage of all of the variable costs (e.g., fuel expenses) it would incur if called upon to perform actual real-time services under this SC.

### 3 Market Design for the Support of SC Trading

As discussed in [9, 14], swing contract trading can be supported by a sequence of linked centrally-managed forward markets whose planning horizons range from years to minutes. Forward markets with very long planning horizons can be used to encourage new capacity investment while forward markets with very short planning
horizons can be used to correct last-minute imbalances between available generation and forecasted real-time net loads.

In practice, US centrally-managed wholesale power markets are operated as two-settlement systems consisting of a day-ahead market (DAM) operating in tandem with a real-time market (RTM). Intra-day forward markets are then opened as needed between the DAM and the RTM to secure additional generation availability for reliability purposes.

In this study we show how an ISO-managed DAM could be designed to support SC trading. The subset \( M \) of market participants with dispatchable services is assumed to be able to fulfill the availability and performance commitments entailed by the sale and purchase of SCs. These entities could include generation companies (GenCos), load-serving entities (LSEs) with curtable loads, demand response resources (DRRs), electric storage devices (ESDs), and dispatchable variable energy resources (VERs). Additional market participants could include non-dispatchable VERs and LSEs with fixed (must-serve) loads.

<table>
<thead>
<tr>
<th></th>
<th>Current DAM</th>
<th>Proposed SC DAM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Similarities</strong></td>
<td>• Conducted day-ahead to plan for next-day operations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• ISO-managed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• MPs can include GenCos, LSEs, DRRs, ESDs, &amp; VERs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Subject to same physical constraints: e.g. transmission, generation, ramping, &amp; power-balance constraints</td>
<td></td>
</tr>
</tbody>
</table>

| **Differences**        | SCUC & SCED                                                                 | Contract-clearing                                                         |
|                        | Location marginal pricing                                                   | Contract-determined prices                                                |
|                        | Payment for next-day service before actual performance                      | Payment for availability now & performance ex post                       |
|                        | Uplift payments (e.g., for UC)                                              | No out-of-market payments                                                 |
|                        | UC, DAM LMPs, & next-day dispatch schedule                                 | Which contracts have been cleared                                         |

**Fig. 2** Comparison of the SC DAM design with current DAM designs

Figure 2 compares our proposed SC DAM design to current DAM designs, highlighting key similarities and differences. To understand this comparison, it is important to understand the following three attributes of SCs.

First, the swing in the contractual terms of SCs permits these contracts to function as both energy and reserve products. This eliminates the need to provide separate pricing and settlement processes for energy versus reserve services.

Second, the two-part pricing of SCs permits full separate market-based compensation for service availability and service performance. The availability price of an
SC compensates the issuer for service availability, while the performance payment method included among the terms of an SC permits the issuer to be compensated ex post for any actual real-time service provision.

Third, SCs permit resources to internally manage unit commitment and generation capacity constraints. By offering an SC into an SC DAM, a resource is guaranteeing the ISO in charge of this SC DAM that it can feasibly perform the services represented in the SC if called upon to do so. The performance payment method $\phi$ can include special incentives and/or penalties designed to ensure the quality of any performed services.

## 4 SC DAM Optimization Formulation

Current DAM designs rely on standard SCUC/SCED optimizations to determine unit commitment, economic dispatch, and pricing solutions. In a sharp break from this practice, we propose a new analytic optimization formulation for the SC DAM that permits the optimal clearing of SCs.

<table>
<thead>
<tr>
<th>Similarities</th>
<th>SCUC</th>
<th>SCED</th>
<th>SC Contract Clearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Both SCUC &amp; SC contract clearing are solved as mixed integer linear programming (MILP) problems subject to physical constraints</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Differences</th>
<th>SCUC</th>
<th>SCED</th>
<th>SC Contract Clearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Objective</td>
<td>Min (Start-Up/Shutdown Costs + No-Load Costs + Dispatch Costs + Reserve Costs)</td>
<td>Min (Dispatch Costs + Reserve Costs)</td>
<td>Min (Availability Cost + Expected Performance Cost)</td>
</tr>
<tr>
<td>• Start-up &amp; shut-down constraints</td>
<td>Yes</td>
<td>No</td>
<td>Start-up/shut-down constraints are implicit in submitted contracts</td>
</tr>
<tr>
<td>• Primary decision variables</td>
<td>Unit Commitment vector</td>
<td>Energy dispatch &amp; reserves</td>
<td>Cleared contracts</td>
</tr>
<tr>
<td>• Settlement</td>
<td>LMPs calculated as SCED dual variables</td>
<td>Availability prices paid for cleared contracts</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 3** Comparison of the SC DAM optimization formulation with SCUC/SCED optimization formulations for current DAMs

Figure 3 highlights key distinctions between our proposed optimization formulation for the SC DAM and traditional SCUC/SCED optimization formulations. This
section clarifies these distinctions by setting out, in concrete analytic terms, our proposed SC DAM optimization formulation.

To simplify the exposition, three assumptions are made. First, it is assumed that all loads serviced by LSEs are fixed (must have) loads, and that all LSE bids have a simple block-energy form, i.e., the bids consist of a quantity demand (MW) for each period $t$ that is not responsive to price. Second, it is assumed that each market participant $m$ with dispatchable services offers only one SC into the SC DAM, and the performance payment method $\phi_m$ appearing within this SC takes the form of a fixed flat rate for energy ($$/MWh$). Third, it is assumed that only system-wide reserve requirements are imposed.

The objective of the ISO managing the SC DAM is to minimize total cost subject to constraints. Total cost is the summation of SC availability cost plus expected performance cost arising from the need to balance next-day net loads as determined by LSE bids and forecasted generation from non-dispatchable VERs. Total cost is expressible as follows:

$$\sum_{m \in M} \alpha_m c_m + \sum_{t \in T} \sum_{m \in M} \phi_m(t) |p_m(t)| \Delta t$$

The ISO minimizes (2) by appropriate selection of the following ISO decision variables:

- **Market participant contract clearing indicators:**
  $$c_m \in \{0, 1\}, \ \forall m \in M$$

- **Market participant power dispatch levels:**
  $$p_m(t), \ \forall m \in M, \ t \in T$$

- **Bus voltage angles:**
  $$\theta_b(t), \ \forall b \in B, t \in T$$

The constraints for the minimization of (2) are as follows:

**ISO decision variable bounds:**

$$c_m \in \{0, 1\}, \ \forall m \in M$$

$$-\pi \leq \theta_b(t) \leq \pi, \ \forall b \in B, t \in T$$

---

2 See [9] for a discussion of the more general case in which offers can take the form of portfolios consisting of multiple SCs.

3 Although power levels for all market participants nominally appear in the objective function (2), it will be seen below that the constraints for the SC DAM optimization formulation restrict the power amounts for market participants with non-cleared SCs to be zero.
Unit commitment constraints:

\[ v_m(t) = c_m \cdot A_m(t), \quad \forall m \in M, \ t \in T \] (5)

Voltage angle specification at angle reference bus 1:

\[ \theta_1(t) = 0, \quad \forall t \in T \] (6)

Line power constraints:

\[ w_\ell(t) = S_{oB}(\ell) \left[ \theta_{O(\ell)}(t) - \theta_{E(\ell)}(t) \right], \quad \forall b \in B, \ell \in L, \ t \in T \] (7)

Transmission constraints:

\[ -F_{\ell}^{\max} \leq w_\ell(t) \leq F_{\ell}^{\max}, \quad \forall \ell \in L, \ t \in T \] (8)

Power balance constraints at each bus:

\[ \sum_{m \in M_b} p_m(t) + \sum_{\ell \in L_{E(b)}} w_\ell(t) = N_{L_b}(t) + \sum_{\ell \in L_{O(b)}} w_\ell(t), \quad \forall b \in B, \ t \in T \] (9)

Market participant capacity constraints:

\[ p_m(t) \leq \bar{p}_m(t) \leq \bar{p}_m(t), \quad \forall m \in M, \ t \in T \] (10)

\[ \bar{p}_m(t) \leq p_m^{\max} v_m(t), \quad \forall m \in M, \ t \in T \] (11)

\[ p_m(t) \geq p_m^{\min} v_m(t), \quad \forall m \in M, \ t \in T \] (12)

Market participant ramp-up and ramp-down constraints:

\[ \bar{p}_m(t) - p_m(t - 1) \leq R^{U}_m \cdot \Delta t v_m(t - 1) + P^{\max}_m \cdot [1 - v_m(t - 1)] \]
\[ \forall m \in M, \ \forall t = 2, \cdots, T \] (13)

\[ p_m(t - 1) - p_m(t) \leq R^{D}_m \cdot \Delta t v_m(t) + P^{\max}_m \cdot [1 - v_m(t)] \]
\[ \forall m \in M, \ \forall t = 2, \cdots, T \] (14)

System-wide reserve requirement constraints:

\[ \sum_{m \in M} \bar{p}_m(t) \geq \sum_{b \in B} N_{L_b}(t) + RR^U(t), \quad \forall t \in T \] (15)

\[ \sum_{m \in M} p_m(t) \leq \sum_{b \in B} N_{L_b}(t) - RR^D(t), \quad \forall t \in T \] (16)
5 More Extended Explanation of the SC DAM Optimization

The absolute value terms |\( p_m(t) \)| in the objective function (2) do not pose any computational difficulty. Because the goal is to minimize this objective function, these absolute value terms can equivalently be represented in terms of linear inequality constraints, as follows:

• Introduce new decision variables for the ISO: \( p^a_m(t), \forall m \in \mathbb{M}, t \in \mathbb{T} \);
• In the objective function (2), replace \( |p_m(t)| \) by \( p^a_m(t), \forall m \in \mathbb{M}, t \in \mathbb{T} \);
• Include the following additional linear inequality constraints in the constraint set:

\[
p^a_m(t) \geq p_m(t) \quad \text{and} \quad p^a_m(t) \geq -p_m, \forall m \in \mathbb{M}, t \in \mathbb{T}.
\] (17)

Any solution for the resulting constrained minimization problem will then require

\[
p^a_m(t) = |p_m(t)|, \forall m \in \mathbb{M}, t \in \mathbb{T}.
\] (18)

As seen in Section 4, the unit commitment constraints take the form

\[
v_m(t) = c_m \cdot A_m(t), \quad \forall m \in \mathbb{M}, t \in \mathbb{T}
\] (19)

The unit commitment \( v_m(t) \in \{0, 1\} \) for each market participant \( m \in \mathbb{M} \) in each time period \( t \) is determined by two factors:

(a) Is \( m \)'s SC offer cleared by the ISO?
(b) Does \( m \)'s SC offer include service for time period \( t \)?

The contract clearing indicator \( c_m \in \{0, 1\} \) represents condition (a), and the offer service indicator \( A_m(t) \in \{0, 1\} \) represents condition (b). If conditions (a) and (b) are both met, then \( m \) is synchronized to the grid in time period \( t \) and can provide service. Otherwise, if at most one of these conditions is met, \( m \) is offline in time period \( t \) and is not able to provide service.

The offer service indicator \( A_m(t) \) is an input to the optimization formulation that is calculated as a function of the SC offered into the SC DAM by market participant \( m \). Consider, for example, the numerical SC example presented in Section 2. In this example, a market participant \( m \) submits an SC consisting of an offer to provide service between 8:00am and 10:00am during the following day. Thus:

\[
A_m(t) = \begin{cases} 
1 & \text{if } t = 8, 9 \\
0 & \text{if } t = 1, \ldots, 7, 10, \ldots, 24 
\end{cases}
\]

As seen in Section 4, the market participant capacity constraints take the form

\[
p_m(t) \leq p_m(t) \leq \bar{p}_m(t), \quad \forall m \in \mathbb{M}, t \in \mathbb{T}
\] (20)

\[
\bar{p}_m(t) \leq P_{\max}^m v_m(t), \quad \forall m \in \mathbb{M}, t \in \mathbb{T}
\] (21)

\[
p_m(t) \geq P_{\min}^m v_m(t), \quad \forall m \in \mathbb{M}, t \in \mathbb{T}
\] (22)
Also, the ramp-up and ramp-down constraints take the form

\[ \bar{p}_m(t) - p_m(t - 1) \leq R^U_m \Delta t v_m(t - 1) + P^\text{max}_m [1 - v_m(t - 1)] \]
\[ \forall m \in M, \forall t = 2, \cdots, T \]  

\[ p_m(t - 1) - \bar{p}_m(t) \leq R^D_m \Delta t \cdot v_m(t) + P^\text{max}_m [1 - v_m(t)] \]
\[ \forall m \in M, \forall t = 2, \cdots, T \]  

The power bounds \( p_m(t) \) and \( \bar{p}_m(t) \) appearing in constraints (20) through (24) are derived values; they give the run-time lower and upper bounds on down/up power availability from market participant \( m \) in each time period \( t \) as a function of the ISO’s unit commitment decisions \( v_m(t - 1) \) and \( v_m(t) \).

More precisely, the unit commitment vector \((v_m(t - 1), v_m(t))\) for each market participant \( m \) in each time period \( t \) can take on only one of four possible value combinations: namely, \((0,0), (1,0), (0,1), \) and \((1,1)\). As indicated in Table 1, for each of these four possible value combinations, constraints (20) through (24) reduce to a distinct set of joint restrictions on \((p_m(t - 1), p_m(t), \bar{p}_m(t), \bar{p}_m(t))\).

<table>
<thead>
<tr>
<th>( v_m(t) )</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_m(t - 1) )</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( \bar{p}_m(t) )</td>
<td>0</td>
<td>0</td>
<td>( \bar{p}_m(t) \leq P^\text{max}_m )</td>
<td>( \bar{p}_m(t) \leq p_m(t) \leq \bar{p}_m(t - 1) + R^U_m \Delta t )</td>
</tr>
<tr>
<td>( p_m(t) )</td>
<td>0</td>
<td>0</td>
<td>( p_m(t) \geq P^\text{min}_m )</td>
<td>( p_m(t) \geq p_m(t) \geq p_m(t - 1) - R^D_m \Delta t )</td>
</tr>
</tbody>
</table>

Finally, it is important to note that an “inherent reserve range” can be derived for the power system in each time period \( t \), as a function of the solution for the SC DAM optimization, as follows. Define

\[ RR^{\text{max}}(t) = \sum_{m \in M} \bar{p}_m(t) \forall t \in T \]  
\[ RR^{\text{min}}(t) = \sum_{m \in M} p_m(t) \forall t \in T \]  

By construction, the MW amounts \( RR^{\text{max}}(t) \) and \( RR^{\text{min}}(t) \) are the maximum and minimum amounts of power available for the system in each time period \( t \) during implementation of the SC DAM optimization solution. The inherent reserve range for time period \( t \) is then given by the interval

\[ IRR(t) = [RR^{\text{min}}(t), RR^{\text{max}}(t)] \]  

(27)
This section reports illustrative SC DAM optimization findings for a simple power system with three dispatchable GenCos and no transmission congestion. Each GenCo submits one SC to the ISO-managed SC DAM, as depicted in Table 2.

### Table 2 SCs submitted by the three GenCos in the Illustrative Example

<table>
<thead>
<tr>
<th>GenCo</th>
<th>Service Period $[t_s, t_e]$</th>
<th>Power Range $[P_{min}, P_{max}]$ (MW)</th>
<th>Ramp Rate Range $[-R^D, R^U]$ (MW/h)</th>
<th>Performance Price $\phi$ ($/MWh$)</th>
<th>Availability Price $\alpha$ ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[1, 24]</td>
<td>[0, 80]</td>
<td>[-60, 60]</td>
<td>25</td>
<td>1500</td>
</tr>
<tr>
<td>2</td>
<td>[1, 24]</td>
<td>[0, 200]</td>
<td>[-30, 30]</td>
<td>10</td>
<td>2000</td>
</tr>
<tr>
<td>3</td>
<td>[8, 24]</td>
<td>[0, 120]</td>
<td>[-50, 50]</td>
<td>20</td>
<td>1000</td>
</tr>
</tbody>
</table>

Time periods $t$ are measured in hours, and the net load for each hour $t$ of the following day is depicted in Fig. 4. The system-wide reserve requirement is set at 10MW above/below net load for each hour $t$, i.e., $RR^U(t) = RR^D(t) = 10$MW for each hour $t$.

The ISO applies an MILP solver to determine an SC DAM optimization solution for the following day, conditional on the three submitted SCs. Simulation results show that the SCs submitted by GenCo 2 and GenCo 3 are cleared: i.e., $c_{m1} = 0$, $c_{m2} = 1$, and $c_{m3} = 1$. The optimal unit commitment $v_m(t)$ and dispatch schedule $p_m(t)$ for each GenCo $m$ in each hour $t$ are shown in Tables 3 and 4, respectively.

The DAM prices for the cleared SCs are their submitted availability prices, and the payments to be received for any actual services performed under these SCs the
following day are based on the energy prices specified by the cleared SC performance payment methods: that is, $\phi_{m2} = $10/MWh and $\phi_{m3} = $20/MWh.

**Table 3** Unit commitment determined by the SC DAM optimization for the illustrative example

<table>
<thead>
<tr>
<th>GenCo</th>
<th>Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24</td>
</tr>
<tr>
<td>1</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>3</td>
<td>0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1</td>
</tr>
</tbody>
</table>

**Table 4** Optimal dispatch scheduling (MWs) determined by the SC DAM optimization for the illustrative example

<table>
<thead>
<tr>
<th>GenCo</th>
<th>Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24</td>
</tr>
<tr>
<td>1</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>2</td>
<td>1 100 90 100 100 110 130 140 150 170 160 150 140 130 160 190 200 180 170 150 130 120 110</td>
</tr>
<tr>
<td>3</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

The results show that GenCo 2 serves as base load due to its relatively low performance price, similar to a coal or nuclear plant. The reasons why GenCo 3’s submitted SC is also cleared are as follows. First, there is a big ramp-up in net load from hour 15 to hour 16. Due to GenCo 2’s limited ramp capability, the maximum available power output for GenCo 2 at hour 16 is 160MW. Thus, GenCo 3 is cleared although it is relatively more expensive. Second, the net load for hour 18 is 210MW, which exceeds GenCo 2’s upper output limit 200MW. Thus, GenCo 3 is needed to provide additional power.

Although GenCo 3’s available power is not used until hour 16, the unit commitment for GenCo 3 in fact spans from hour 8 to hour 24. The reason for this is that GenCo’s SC commits this GenCo to be available to provide power from hour 8 through hour 24. Thus, if the ISO clears the contract, GenCo 3 must be synchronized to the grid during each of these hours.

Figure 5 depicts the inherent reserve range resulting from the cleared SCs for GenCo 2 and GenCo 3, together with the down/up reserve requirements. The inherent reserve range is represented by solid lines and the down/up reserve requirements are represented by dashed lines. Note that the reserve range satisfies the down/up reserve requirements while at the same time providing valuable flexibility to the ISO for use in real-time balancing operations.
7 Conclusion

A new MILP optimization formulation has been proposed and demonstrated for an ISO-managed DAM based on swing contracts for the combined flexible provision of energy and reserve services. In future work we will extend this formulation to encompass combined DAM/RTM operations, and we will undertake systematic feasibility and cost comparisons with existing DAM/RTM operations. In addition, we will explore the potential of swing contracts, offered into wholesale power markets by managers of distributed resources, to facilitate the integrated operation of transmission and distribution systems.

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References

strained optimal power flow. Electric Power Systems Research 81(8):1731-1741
Appendix

Table 5  Nomenclature listing symbols and symbol descriptions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sets and Intervals:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>Set of bus indices $b$</td>
</tr>
<tr>
<td>$L \subset B \times B$</td>
<td>Set of transmission line indices $\ell$</td>
</tr>
<tr>
<td>$L_{O(b)} \subset L$</td>
<td>Subset of lines $\ell$ originating at bus $b$</td>
</tr>
<tr>
<td>$L_{E(b)} \subset L$</td>
<td>Subset of lines $\ell$ ending at bus $b$</td>
</tr>
<tr>
<td><strong>M</strong></td>
<td>Set of indices $m$ for market participants (MPs) with dispatchable services</td>
</tr>
<tr>
<td>$M_{b} \subset M$</td>
<td>Market participants at bus $b$ with dispatchable services</td>
</tr>
<tr>
<td><strong>Interval of power levels $p$ offered in a swing contract</strong></td>
<td>$P$</td>
</tr>
<tr>
<td><strong>Interval of ramp rates $r$ offered in a swing contract</strong></td>
<td>$R$</td>
</tr>
<tr>
<td><strong>Set of time period indices $t = 1, \ldots, T$</strong></td>
<td>$T$</td>
</tr>
<tr>
<td><strong>Parameters and Functions:</strong></td>
<td></td>
</tr>
<tr>
<td>$A_{m}(t)$</td>
<td>1 if $m$ in time period $t$ is within its contract service period; 0 otherwise</td>
</tr>
<tr>
<td>$B(\ell)$</td>
<td>Inverse of reactance (pu) for line $\ell$</td>
</tr>
<tr>
<td>$E(\ell)$</td>
<td>End bus for line $\ell$</td>
</tr>
<tr>
<td>$F_{\text{max}} \ell$</td>
<td>Power limit (MW) for line $\ell$</td>
</tr>
<tr>
<td>$NL_{b}(t)$</td>
<td>Net load (MW) at bus $b$ in time period $t$</td>
</tr>
<tr>
<td>$O(\ell)$</td>
<td>Originating bus for line $\ell$</td>
</tr>
<tr>
<td>$p_{\text{min}} m$</td>
<td>Lower power limit (MW) of $m$</td>
</tr>
<tr>
<td>$p_{\text{max}} m$</td>
<td>Upper power limit (MW) of $m$</td>
</tr>
<tr>
<td>$R_{D}^{\ell} m$</td>
<td>Ramp-down limit (MW/$\Delta t$) of $m$</td>
</tr>
<tr>
<td>$R_{U}^{\ell} m$</td>
<td>Ramp-up limit (MW/$\Delta t$) of $m$</td>
</tr>
<tr>
<td>$RR_{D}(t)$</td>
<td>System-wide down reserve requirement (MW) in time period $t$</td>
</tr>
<tr>
<td>$RR_{U}(t)$</td>
<td>System-wide up reserve requirement (MW) in time period $t$</td>
</tr>
<tr>
<td>$S_{o}$</td>
<td>Positive base power (in three-phase MVA)</td>
</tr>
<tr>
<td>$t_{e}$</td>
<td>Power delivery end time offered in a swing contract</td>
</tr>
<tr>
<td>$t_{s}$</td>
<td>Power delivery start time offered in a swing contract</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Time-period length</td>
</tr>
<tr>
<td>$\alpha_{m}$</td>
<td>Availability price ($) requested by $m$ for a swing contract offering service availability</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Performance payment method for real-time service offered in a swing contract</td>
</tr>
<tr>
<td>$\phi_{m}(t)$</td>
<td>Performance price ($$/MW\Delta t$) requested by $m$ for the ex post compensation of down/up power delivery in time period $t$ in illustrative examples</td>
</tr>
<tr>
<td><strong>SC DAM Optimization Variables:</strong></td>
<td></td>
</tr>
<tr>
<td>$c_{m}$</td>
<td>1 if the swing contract offered by $m$ is cleared; 0 otherwise</td>
</tr>
<tr>
<td>$v_{m}(t)$</td>
<td>1 if $m$ is online in time period $t$; 0 otherwise</td>
</tr>
<tr>
<td>$p_{m}(t)$</td>
<td>Power output (MW) of $m$ in time period $t$</td>
</tr>
<tr>
<td>$P_{m}(t)$</td>
<td>Maximum available power output (MW) of $m$ in time period $t$</td>
</tr>
<tr>
<td>$P_{m}(t)$</td>
<td>Minimum available power output (MW) of $m$ in time period $t$</td>
</tr>
<tr>
<td>$\theta_{b}(t)$</td>
<td>Voltage angle (radians) at bus $b$ in time period $t$</td>
</tr>
<tr>
<td>$w_{\ell}(t)$</td>
<td>Line power (MW) for line $\ell$ in time period $t$</td>
</tr>
</tbody>
</table>